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A Resistance Thermometer for Measurement of Rapid Air Temperature Fluctuations

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A RESISTANCE THERMOMETER FOR MEASUREMENT OF RAPID AIR TEMPERATURE FLUCTUATIONS

Gerard R. Ochs

A resistance thermometer capable of measuring air temperature fluctuations in the frequency range 0.05 to 2000 Hz with a sensitivity of 0.1^{o}C is described. Experimental tests to verify the accuracy of a measurement of this type are described.

1. INTRODUCTION

The study of atmospheric turbulence is receiving increased attention from two relatively new fields; micrometeorology and optical propagation. In these studies, the measurement of small-scale atmospheric temperature variations, both spatial and temporal, is necessary for a more complete understanding of the physical processes of turbulent air movement in the atmosphere. Such measurement may be expected to lead to a better understanding of the limitations to optical propagation through the atmosphere; this was the incentive for the development of the instrument to be described.

Atmospheric turbulence has concerned optical astronomers for many years, since it places a severe limitation on the definition of telescopes, especially those of large aperture. More recently, with the advent of lasers and the possibility of wide-band communication at optical carrier frequencies, there has been renewed interest in the effects of atmospheric turbulence upon light transmission. The fluctuations in air density, because of turbulence, result in changes in the index of refraction and therefore affect the angular spectrum of the optical wave front propagating through the atmosphere. Since variations in air pressure propagate with the speed of sound, they do not contribute significantly to the small-scale density inhomogeneities in the atmosphere. Rather, temperature variations are responsible for the density inhomogeneities and hence the deleterious effects upon optical images (Briggs, 1963). Ideally, an instrument for measuring these variations should be capable of measuring temperature at a point in the atmosphere without itself altering the temperature. Directly measuring the index of refraction by optical interferometry seemed attractive at first, because no heat exchange is required to make the measurement. Unfortunately, measuring small volumes of air involves the proximity of large pieces of glass, which disturb the air flow. An alternative approach involves the temperature measurement of a solid in near equilibrium with the surrounding air. A study of the performance of a resistance thermometer indicates that this means of air temperature measurement is sufficiently close to the ideal to be useful.*

2. DESCRIPTION OF THE INSTRUMENT

Basically, the instrument is a resistance thermometer connected to an amplifier having a maximum gain of 10^5 and a 16-kHz bandpass. A circuit diagram is shown in figure 1. A calibration circuit and a switch to remove the low-frequency cutoff have been included.

The resistance-sensing element is a length of Wollaston process platinum wire 0.63μ in diameter and 1 mm or less in length. A 120V pilot light bulb with its envelope and filament removed has been used as a convenient base for mounting the wire. These elements are fragile but, when new, clean, and dust free, they will not break in winds up to 11 m/sec (25 mph).

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* Since the completion of this study, we found that a similar study has been made using a platinum-rhodium wire 0.6μ in diameter. This work is described in an unpublished report by J. L. Chao and V. A. Sandborn, Colorado State University, 1964.

In the Wollaston process, platinum wire is encased in a silver tube and the combination is drawn through a die. In this way, extremely small diameter wire can be made. The wire is furnished encased in the silver, and it is handled and mounted in this form on the lead-in wires originally connected to the lamp filament. When the mounting is completed, the silver is etched off with nitric acid, leaving the fine platinum filament.

The calibration arrangement is incorporated into the measurement current supply. Referring to figure 1, by changing the measuring current slightly by removal or insertion of known ΔR, it is possible to change V_f by the amount, ΔV_f, that would occur through a temperature change, ΔT, in the filament. Hence, this may be used as a calibration technique as long as the filament current, I , is small enough so that R_f does not change due to self-heating. Thus holding I constant,

$$\Delta T = \frac{\Delta V_f}{\alpha I R_f} \quad \text{for} \quad \begin{matrix} R \gg \Delta R \\ R \gg R_f \end{matrix} \qquad \alpha = \text{temperature coefficient of resistance of filament.}$$

and

$$\Delta V_f = \Delta T \alpha I R_f \tag{1}$$

But V_f may also be changed by changing I so

$$V_f = I R_f$$

and

$$\Delta V_f = -I R_f \frac{\Delta R}{R} \tag{2}$$

Equating (1) and (2), we find

$$\Delta T \alpha I R_f = -I R_f \frac{\Delta R}{R}$$

or

$$\Delta T = - \frac{\Delta R}{\alpha R} \tag{3}$$

Note that R_f does not appear in (3) . Thus as long as $R >> R_f$, filament length differences have no significant effect on the calibration.

The input impedance of the amplifier is 1000 ohms, nearly equal to R_f. The amplifier impedance has not been brought into the calculation, since it presents the same load to both the calibrating signal and the temperature induced signal and thus does not affect the calibration. The resistors in the circuit of figure 1 have been chosen so actuation of the switches shown produce step changes in the amplifier output corresponding to -2°, -1°, $+1^{\circ}$, $+2^{\circ}$ C temperature difference in a platinum filament. These calibrations are based upon $\alpha = 0.003$ for platinum. The overall calibration has been verified by measurements made with the filament immersed in an oil bath of controlled temperature. Since α is also a function of temperature, this calibration strictly applies to $20^{\circ}C$ only, and corrections are necessary at other temperatures. The absolute calibration is not critical for most atmospheric measurements, however, and one calibration is probably sufficient for this purpose.

3. VERIFICATION OF TEMPERATURE MEASUREMENT

As with all instrumentation, it is important to examine critically just what is being measured and how close this quantity approaches the measurement actually desired. For a resistance thermometer to measure accurately microtemperature fluctuations in the atmosphere,

(1) the heat conduction between the air and the resistance element should be high enough to follow any air temperature change expected, (2) the thermal capacity of the resistance element should be small compared to the thermal capacity of the smallest volume of air of interest, (3) the radiation should not be an important factor, (4) the conduction between the filament and the filament supports should be negligible, (5) the supporting structure should not alter the natural flow of air, and (6) the increase in filament temperature due to the measuring current should be small compared to the temperature variations of interest.

These points were investigated using a straight platinum filament 3.3×10^{-2} cm long and 6.35×10^{-5} cm in diameter. This filament has a mass of 9.46×10^{-9} gm and a thermal capacity of 3.07×10^{-10} cal $^{\circ}C^{-1}$. The volume of air at room temperature and atmospheric pressure that has equal thermal capacity is 1.07×10^{-6} cm^3. The dimensions of this volume of air are small compared to the normally accepted values for the inner scale of turbulence in the atmosphere. In fact, a cube of this volume has an edge dimension smaller than the length of the filament, so the filament length determines the spatial resolution of the temperature measurement.

To measure thermal response time, it was necessary to resort to indirect methods. To heat the filament and then observe the time decay of the filament temperature is more informative than to blow heated air over the filament, since there is no independent way to measure the actual temperature gradient. The process of heating the filament and observing its temperature rise to equilibrium relative to the surrounding air is a reversal of the normal situation and its validity can be questioned. If the filament is heated with radiant energy, the heat is applied on the surface, just as it would be if heated by the air. In the case of electrical heating, the heat is produced throughout the volume of the filament, but during its conduction to the surface the temperature gradient in the filament must be very similar to that during external cooling of the surface. In any event, the thermal conductivity of the metal is more than 10^3 times that of air, therefore the temperature gradient inside the wire is small compared to that in the surrounding air.

Two techniques were used to measure the thermal response time. In the first, an electrical current considerably larger than that used to measure resistance was suddenly applied to the filament in a bridge circuit. The rise time of the filament temperature to that required for constant heat transfer to the surroundings was measured. The time constant (time required for the filament temperature to rise to $1-1/e$ of its final value) of the filament thus measured was 250 μsec. The filament was enclosed in a 250-ml flask to help stabilize air temperature fluctuations.

The time response of the filament largely depends upon the effective thermal conductivity of the air. The thermal conductivity of the filament itself is much greater than that of air, so that during a sharp temperature change almost all of the resulting temperature gradient is in the air. Thus, movement of air steepens this gradient resulting in more rapid filament response. The variation in time constant due to wind velocity is shown in figure 2. Since the filament response to a step function input is exponential, the curve in figure 2 is readily transformed into a set of frequency response curves for various wind velocities. This has been done in figure 3 for wind velocities of 0, 0.5, 1, 2, 4 m/sec.

In the second technique, the filament was heated by radiant energy. A helium-neon laser, square-wave intensity modulated at 200 Hz was focussed on the filament inside a 250-ml flask. The exponential rise and decay of the filament temperature, in response to this pulsed radiant energy, had a measured time constant of 220 μsec, slightly shorter than the average determined by the electrical heating technique for the same filament.

The temperature calibration system is relatively unaffected by different filaments or by aging of a particular filament. The time response does vary, however, probably due to varying amounts of foreign matter on the surface of the filament. The values shown in figure 2 and 3 represent the slowest responses encountered and appear to be typical for filaments that have been used outdoors for several hours. Time constants as fast as 80 μsec in still air have been measured for freshly etched filaments.

Figure 4 shows the temperature rise of the filament versus the energy input to it. The self-heating error introduced by the measuring current causes an offset, which in itself would not be objectionable. In the fashion of a hot-wire anemometer, however, the offset temperature is a function of wind velocity and therefore limits the accuracy of the turbulence measurement. In the instrument described here, the offset temperature is about 0.08°C. The rms noise level of the system, due to the resistance of the filament and the input noise level of the amplifier, corresponds to an rms temperature fluctuation of about 0.03°C.

Heat is exchanged between the filament and its surroundings by conduction and convection into the surrounding air, the desired route, and also by undesired paths, viz., by conduction through the filament supports and by radiation. To assess the importance of these latter paths, we again put the filament into a 250-ml flask with the air evacuated to a pressure of 0.2 mm Hg. The pressure was then slowly increased, and the time constant was measured periodically. Figure 5 is a plot of the reciprocal of the temperature time constant versus air pressure in the millimeter range. By extrapolating to zero pressure, a time constant may be estimated for heat exchange by mechanisms other than conduction and convection to air. This value, 30 msec, is more than 100 times the time constant of the sensor at atmospheric pressure.

The change in air flow caused by the filament support wires has not been evaluated. Certainly the much higher thermal capacity of the supports influences the flow of air over the filament, but the amount of change is difficult to evaluate experimentally.

Energy exchange through radiation is inconsequential compared to other mechanisms. This is indicated by the tests at reduced air pressure. The temperature rise due to direct sunlight may be calculated by multiplying the energy density of sunlight times the projected area of the filament. Assuming perfect absorption, we find the maximum energy input to the filament is 0.26 μW. From figure 4, this corresponds to a temperature rise of 0.007°C. When the filament is exposed to direct sunlight, the small temperature rise is not detectable, which would be expected.

The problem of determining the temperature field surrounding a cylinder immersed in an infinite heat sink of different temperature is not a trivial one. To make another estimate of the volume of air involved in the temperature measurement, an approximation to the actual problem was calculated as follows: If the air surrounding the filament is assumed to be in the form of a cylinder concentric with the filament, with the outer wall of the cylinder of radius r_2 at temperature θ_2 and the surface of the filament of radius r_1 at θ_1, then the radius of this cylinder of air may be calculated from the relationship (Zemansky, 1951)

$$\theta_1 - \theta_2 = \frac{\frac{dQ}{d\tau}}{2\pi Lk} \ln \frac{r_2}{r_1} ,$$

where

$$\frac{dQ}{d\tau} = \text{rate of heat flow}$$

L = length of cylinder

k = thermal conductivity of air .

Evaluating this expression with the aid of figure 4 and solving for r_2, we find the radius of the cylinder of air is 1.9×10^{-3} cm . The volume of this cylinder is 1.6×10^{-6} cm^3. This result agrees reasonably well with the earlier calculation showing that the volume of air having thermal capacity equal to that of the filament was 1.07×10^{-6} cm^3.

4. RESULTS

Some measurements using the instrument are shown in figures 6 and 7. Figure 6 shows two samples of temperature variations occurring in a turbulent wind flowing at 3.5 m/sec in the laboratory. Figure 7 shows the vertical space correlation of two temperature sensors spaced at 1, 4, and 16 cm outdoors. The wind was 0.5 to 2.5 m/sec in bright sunlight with the average temperature 25°C and the humidity 24%. The sensors were approximately 70 cm above dry grass ground cover. One sensor output has been applied to the vertical deflection of an oscilloscope and the other to the horizontal deflection. The cross-correlation of the two signals may be estimated from a presentation of this type (Sugar, 1954).

ACKNOWLEDGEMENTS

Robert S. Lawrence suggested the need for a device of this type and the general approach to the problem. I acknowledge the helpful discussions and suggestions of Mr. Lawrence and Dr. C. Gordon Little.

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Zemansky, M. W. (1951), "Heat and Thermodynamics," 3rd ed. (McGraw-Hill Book Co.), New York, New York.

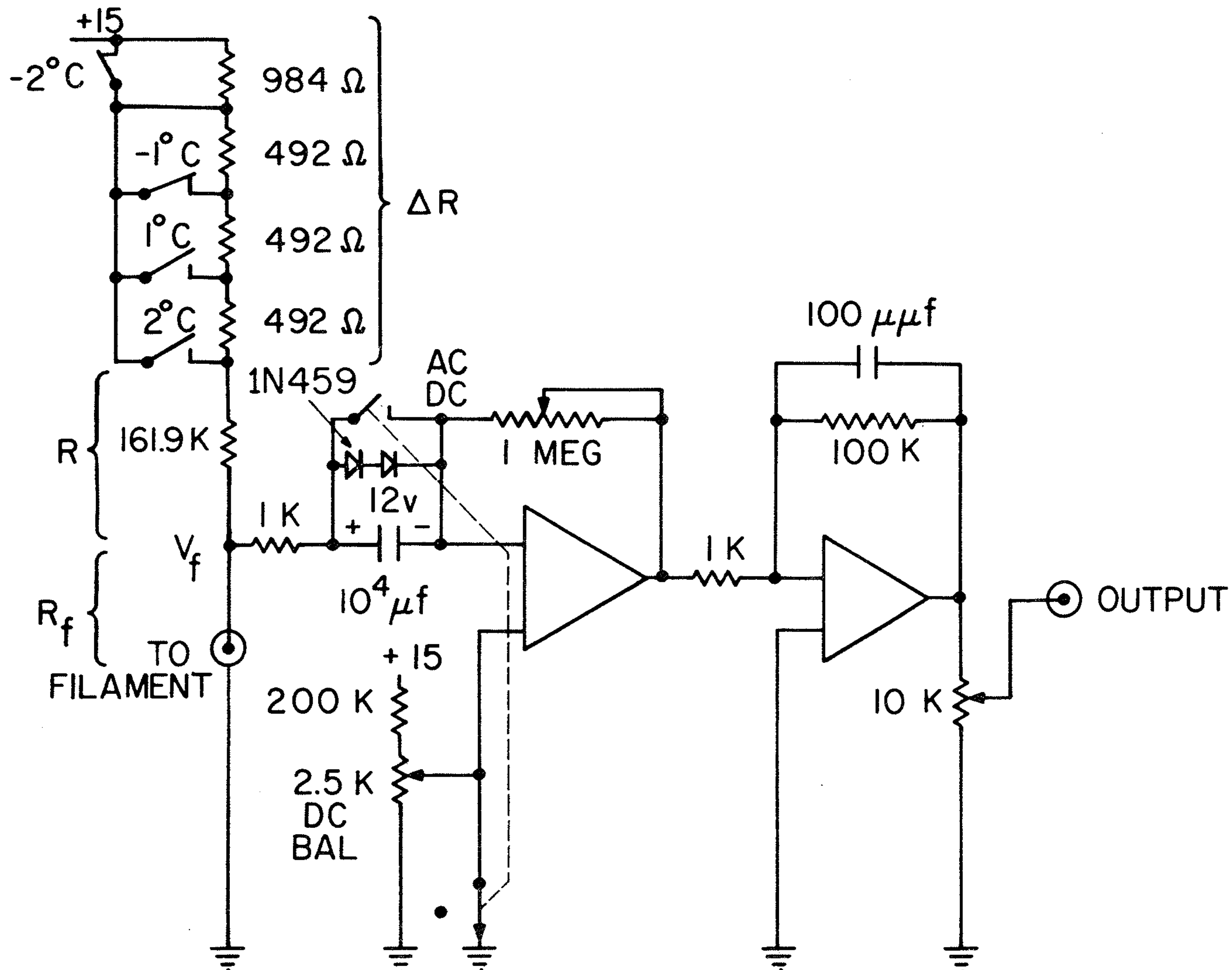

Figure 1. Resistance thermometer amplifier

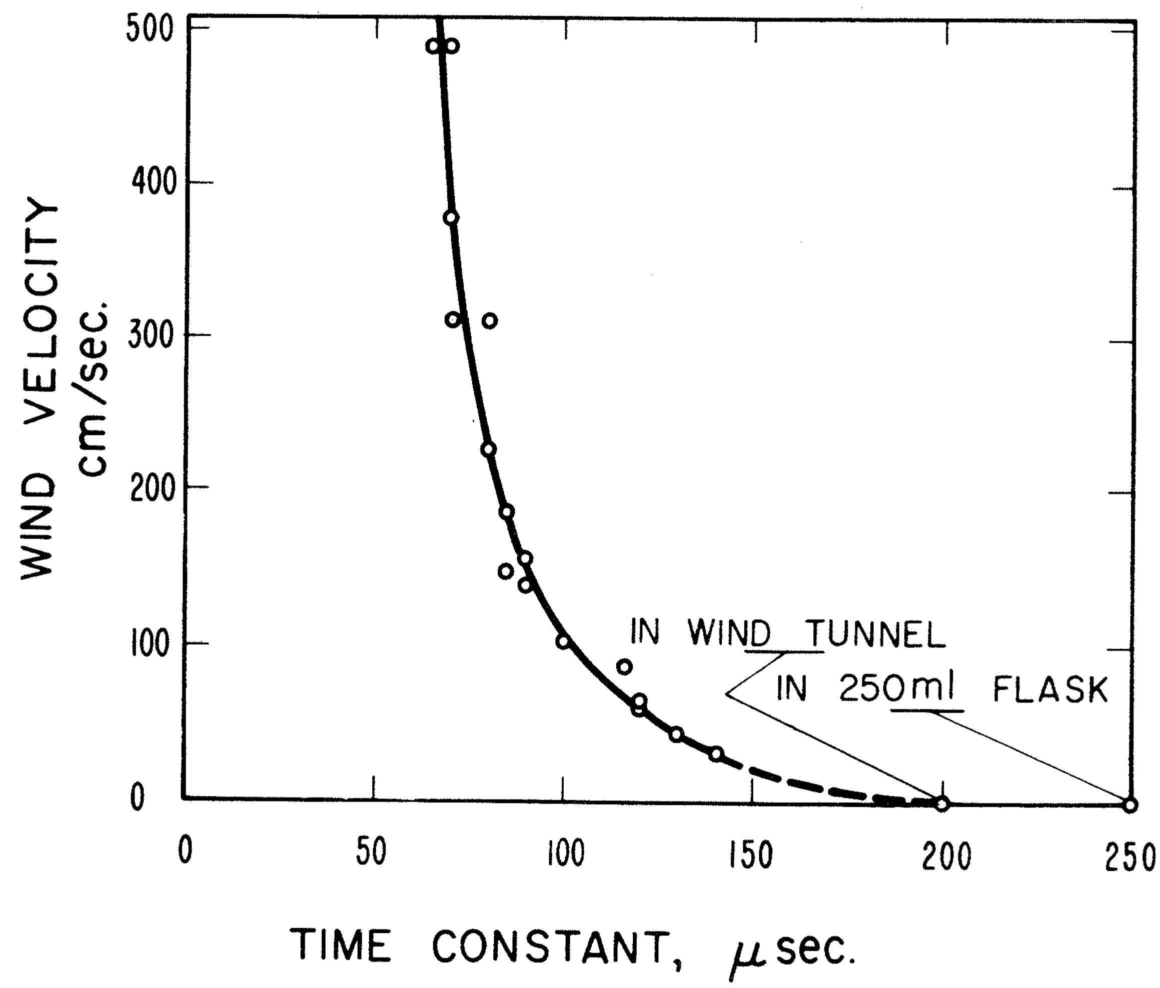

Figure 2. Temperature time constant as a function of wind velocity.

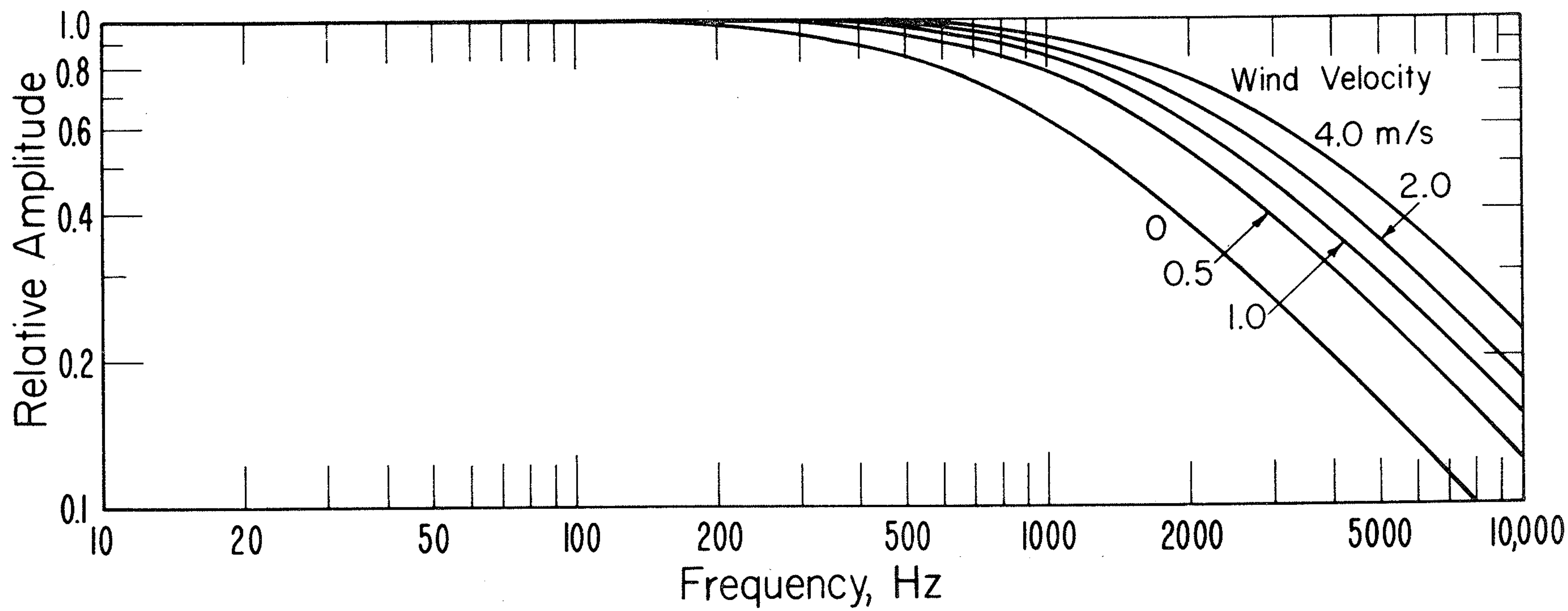

Figure 3. Frequency response of resistance thermometer to air temperature changes.

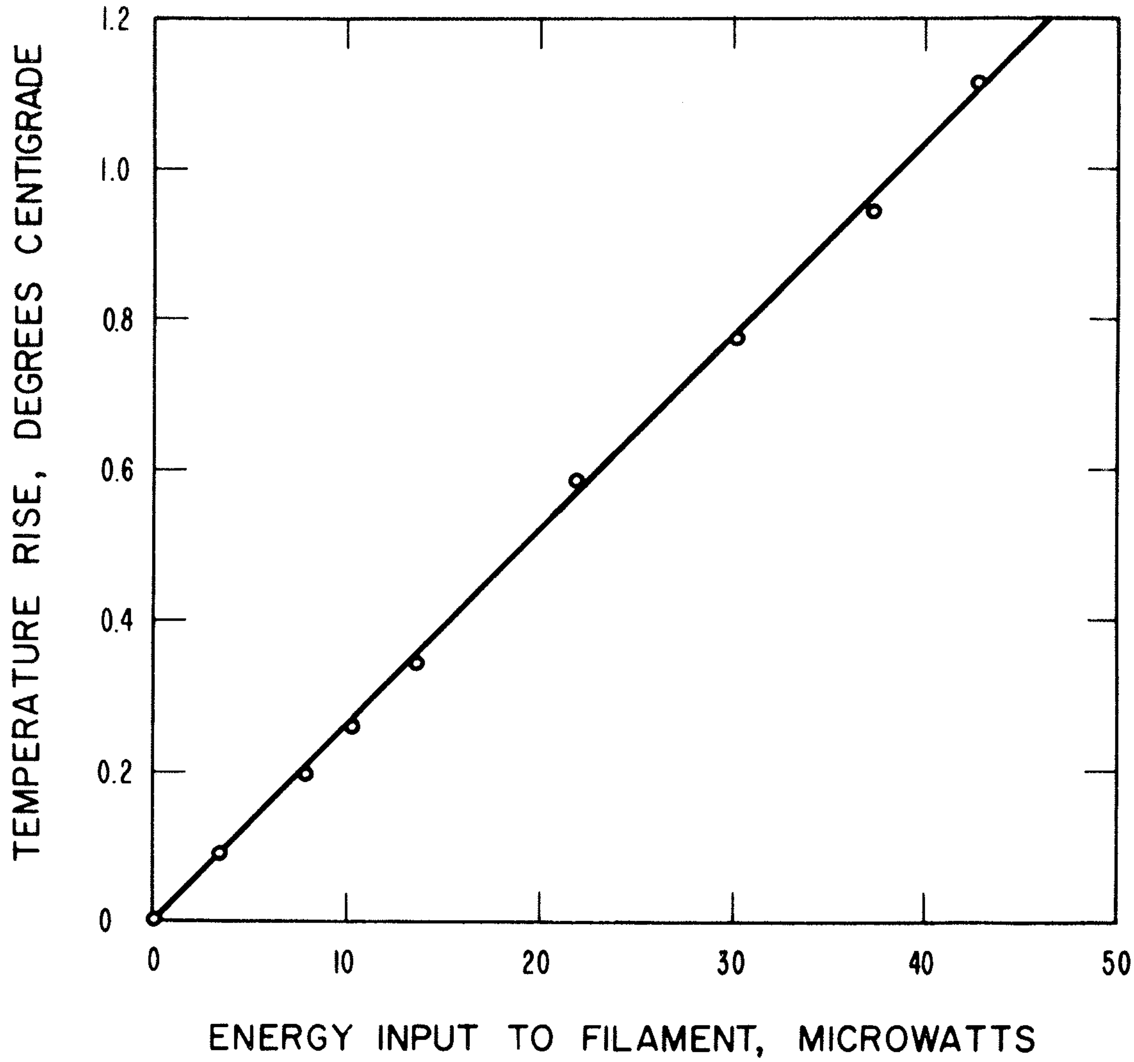

Figure 4. Temperature rise versus energy input to the filament.

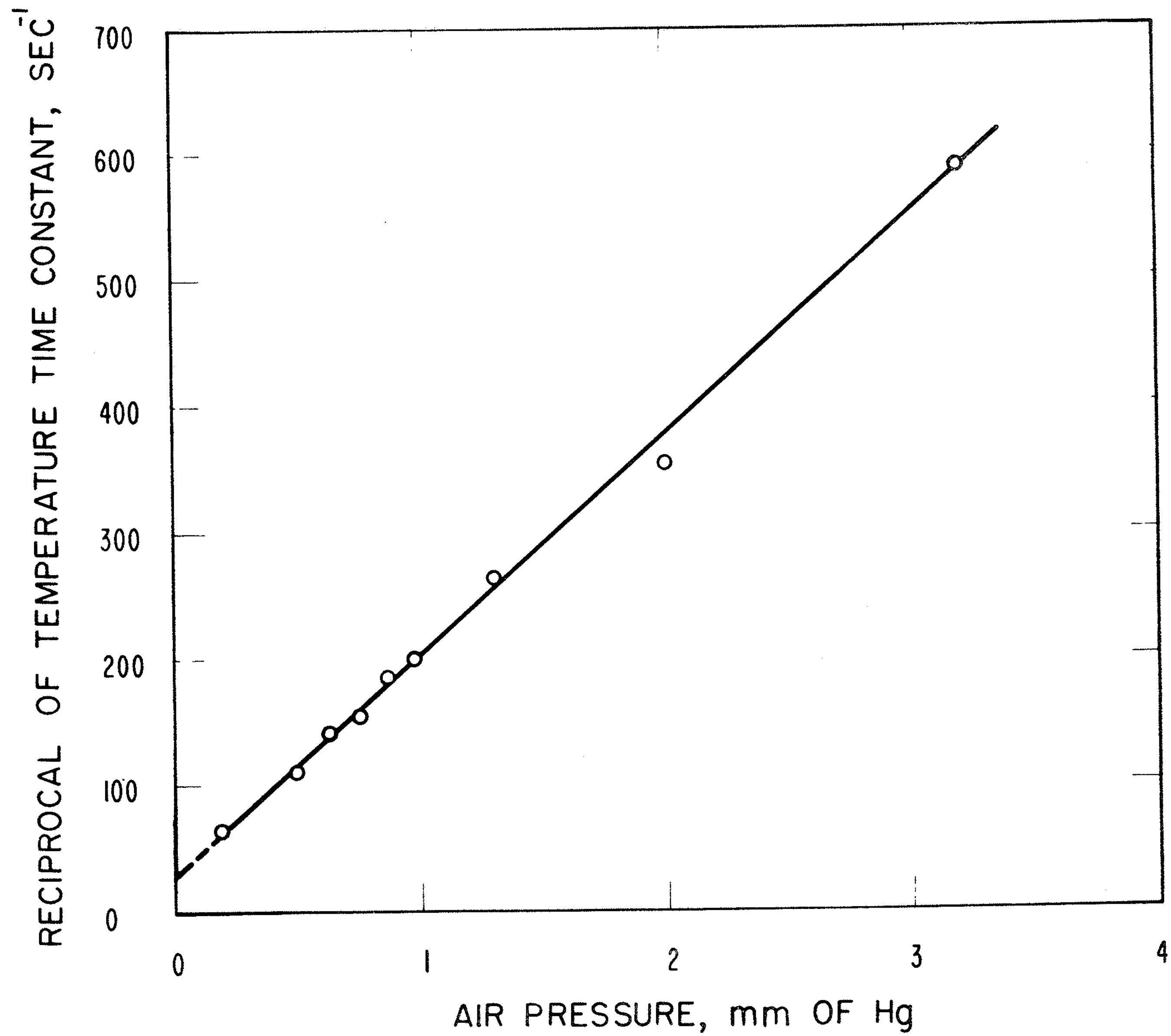

Figure 5. The reciprocal of the temperature time constant versus air pressure. The dotted portion of the line is an extrapolation.

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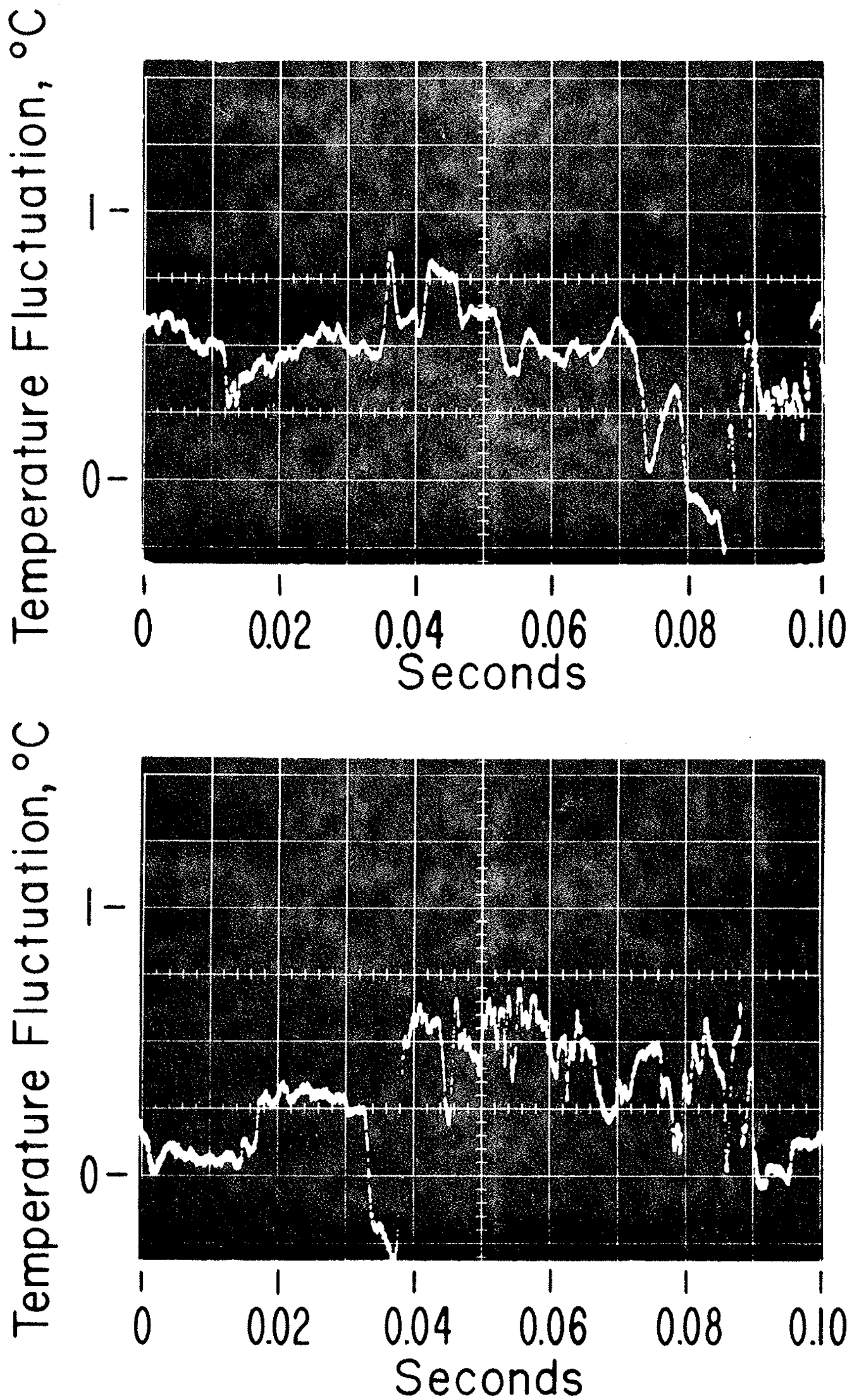
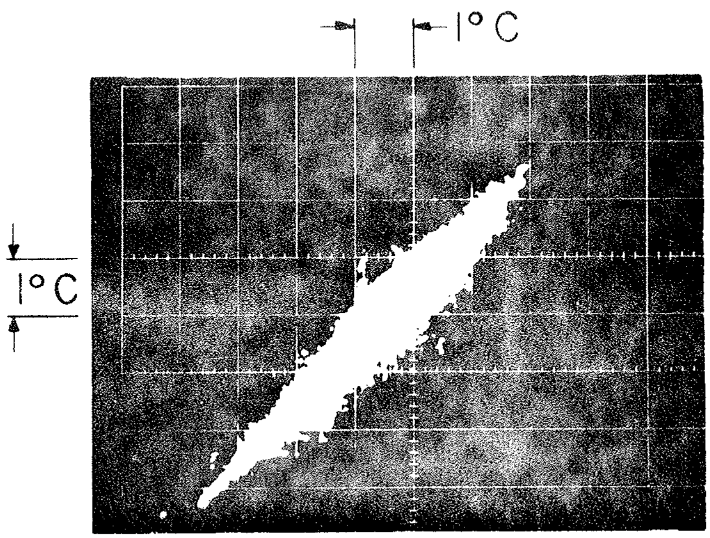
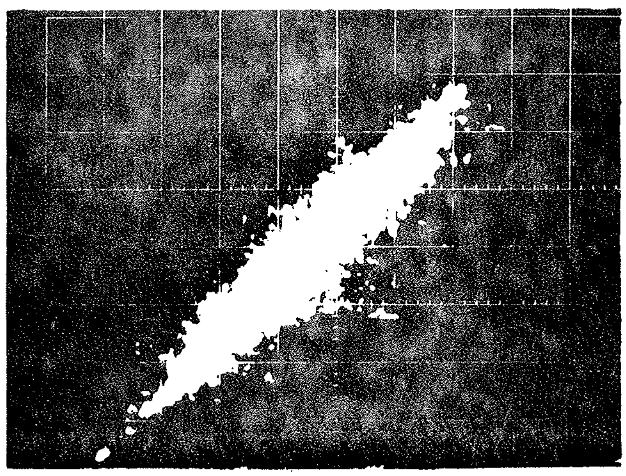


Figure 6. Temperature fluctuations in a 3.5 m/sec air flow in the laboratory.

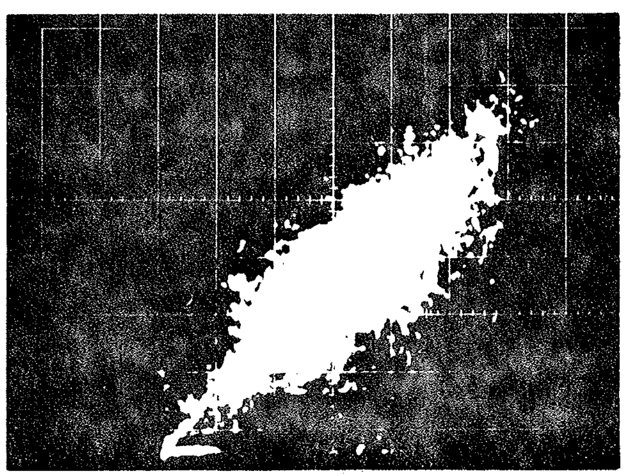
Figure 7. Vertical space correlation of temperature outdoors. The temperature scale is 1°C per division.



Vertical Spacing 1 cm



Vertical Spacing 4 cm



Vertical Spacing 16 cm